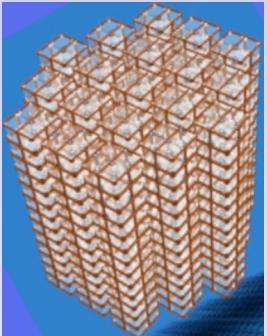
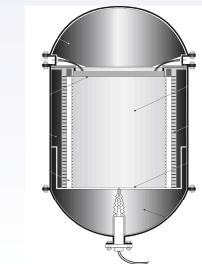
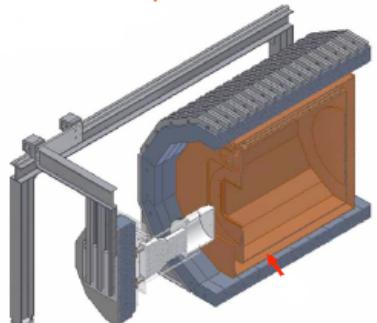
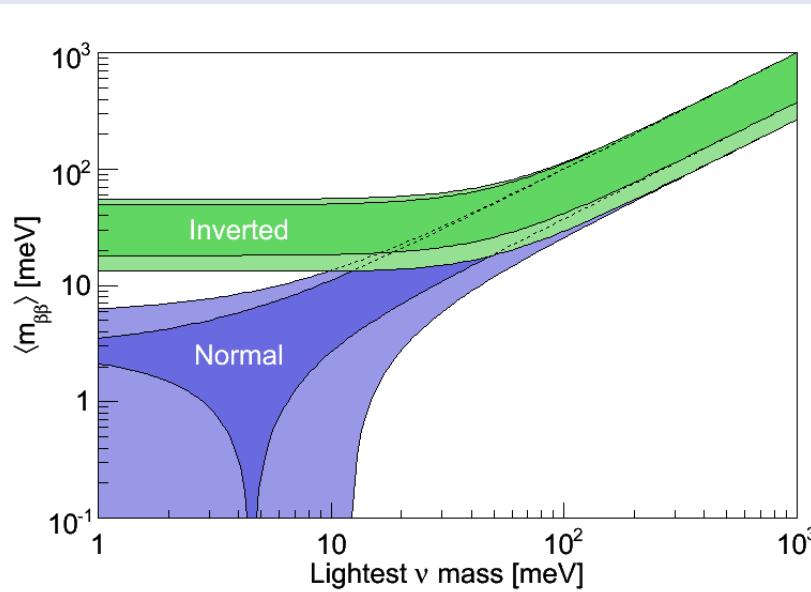
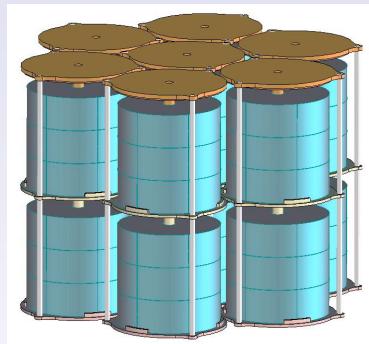
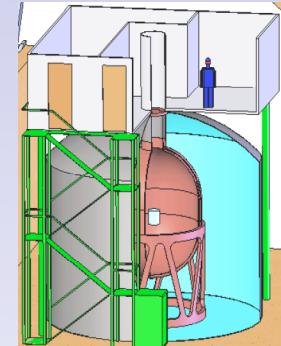


# Neutrinoless Double Beta Decay *past, present, future*



Historical Perspective  
Double Beta Decay Today  
Current & Future Efforts



# Renewed Impetus for $0\nu\beta\beta$

The discovery that neutrinos are not massless particles, provides compelling arguments for performing neutrinoless double-beta decay ( $0\nu\beta\beta$ ) experiments with increasing sensitivity.

## $0\nu\beta\beta$ decay probes fundamental questions:

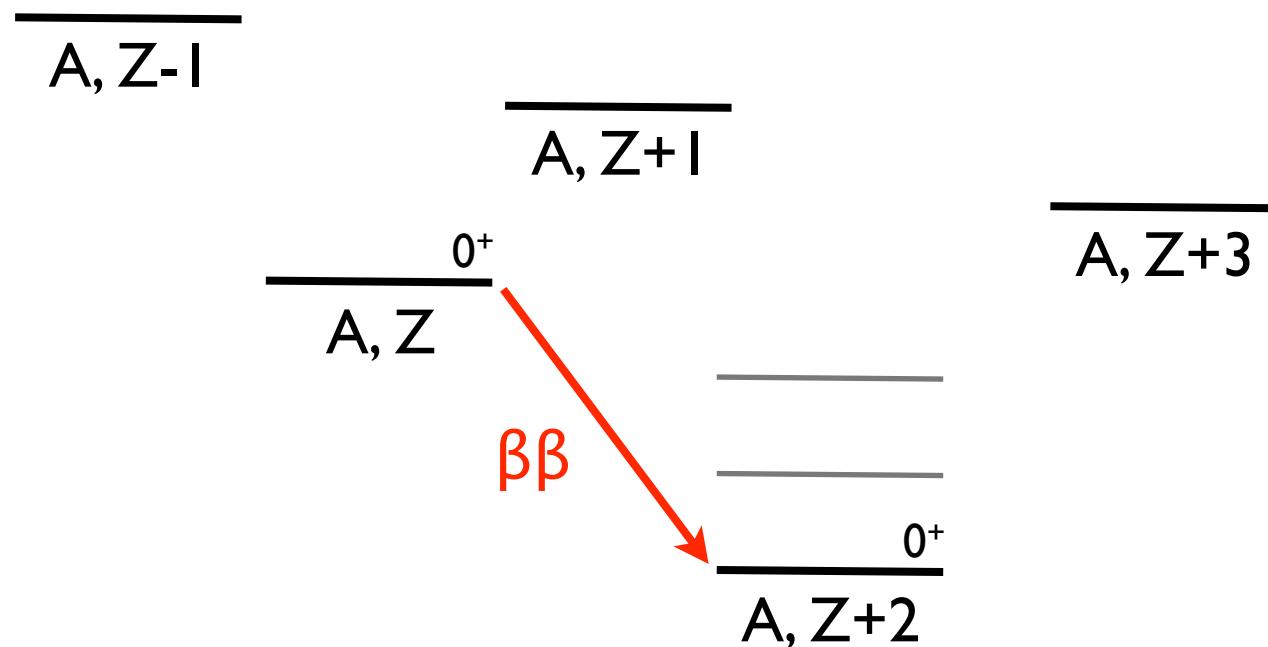
- Lepton number conservation — might Leptogenesis be the explanation for the observed matter - antimatter asymmetry?
- Neutrino properties — the only practical technique to determine if neutrinos are their own anti-particles — Majorana particles.

## If $0\nu\beta\beta$ is observed:

- Provides a promising laboratory method for determining the absolute neutrino mass scale that is complementary to other measurement techniques.
- Measurements in a series of different isotopes potentially can reveal the underlying interaction process(es).

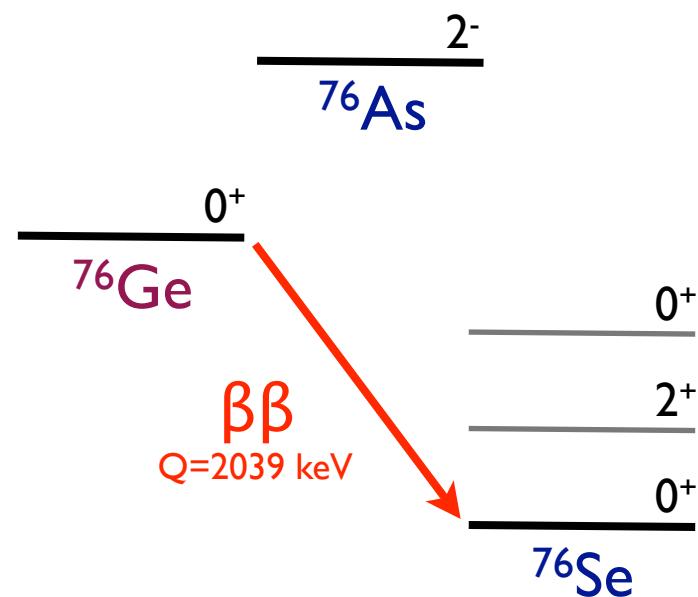
# Double-Beta Decay

In a number of even-even nuclei,  $\beta$ -decay is energetically forbidden, while double-beta decay, from a nucleus of  $(A,Z)$  to  $(A,Z+2)$ , is energetically allowed.



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$^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$   $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$   $^{128}\text{Te}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$

# Double-Beta Decay Modes

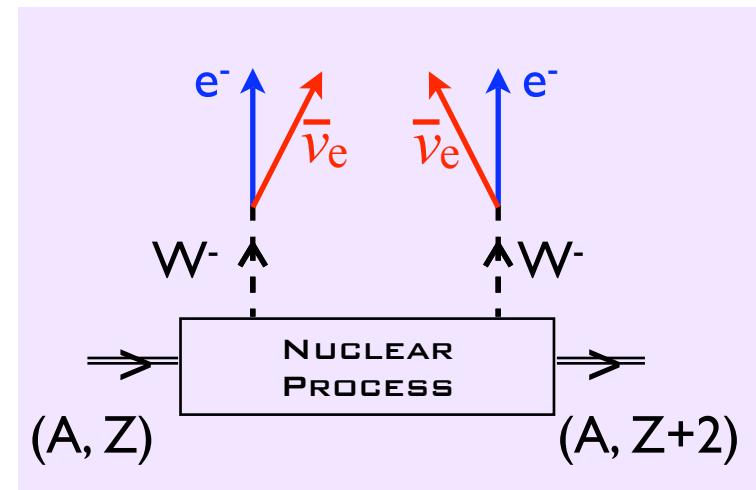
**$2\nu$  double-beta decay ( $2\nu\beta\beta$ ): Nucleus (A, Z)  $\rightarrow$  Nucleus (A, Z+2) + e<sup>-</sup> +  $\bar{\nu}_e$  + e<sup>-</sup> +  $\bar{\nu}_e$**



Allowed second-order  
weak process

Maria Goeppert-Mayer  
(1935)

$2\nu\beta\beta$  observed for  
 $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{128}\text{Te}$ ,  $^{130}\text{Te}$ ,  $^{150}\text{Nd}$



**$0\nu$  double-beta decay ( $0\nu\beta\beta$ ): Nucleus (A, Z)  $\rightarrow$  Nucleus (A, Z+2) + e<sup>-</sup> + e<sup>-</sup>**



Ettore Majorana (1937)  
realized symmetry properties  
of Dirac's theory allowed the  
possibility for electrically  
neutral spin-1/2 fermions to  
be their own anti-particle

# Double-Beta Decay Modes

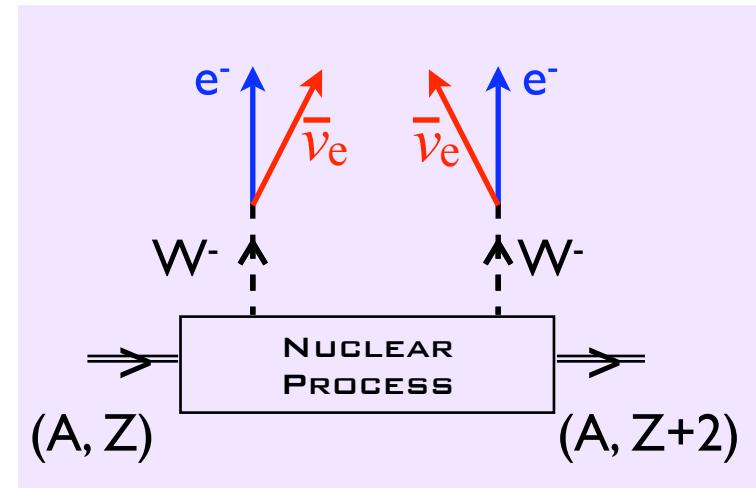
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Allowed second-order  
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Maria Goeppert-Mayer  
(1935)

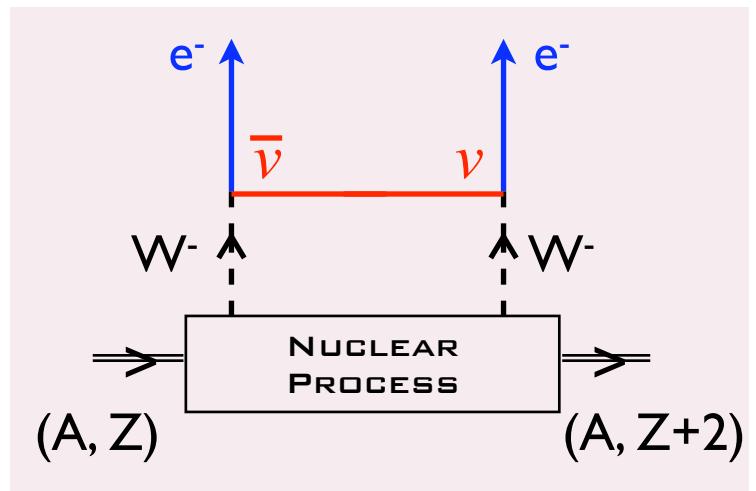
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**$0\nu$  double-beta decay ( $0\nu\beta\beta$ ): Nucleus (A, Z)  $\rightarrow$  Nucleus (A, Z+2) + e<sup>-</sup> + e<sup>-</sup>**

Racah (1937),  
Furry (1938)

$$\begin{aligned} n &\rightarrow p + e^- + \bar{\nu} \\ \nu + n &\rightarrow p + e^- \end{aligned}$$



# Early Estimates of $\beta\beta$ Decay Rates

## 2 $\nu$ double-beta decay ( $2\nu\beta\beta$ )

Maria Goeppert-Mayer (1935)  
using Fermi Theory

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (4-body)} \propto Q^{10-12}$$

$$T_{1/2}^{2\nu\beta\beta} \approx 10^{25} \text{ years}$$

## 0 $\nu$ double-beta decay ( $0\nu\beta\beta$ )

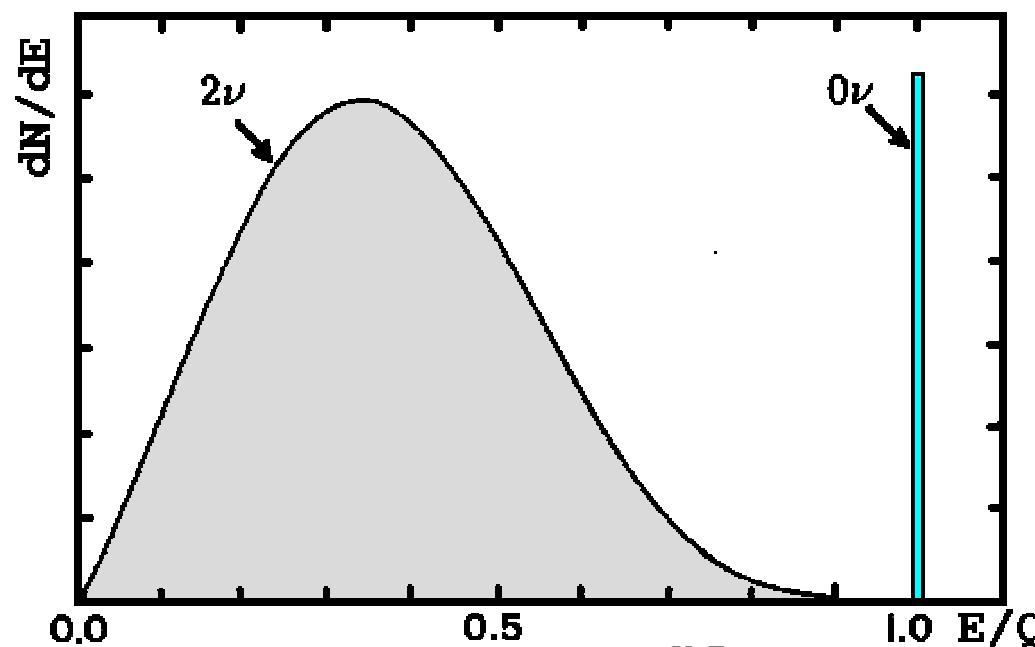
Furry (1939), assuming Parity  
conserved, so no preferential handedness

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (2-body)} \propto Q^5$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{19} \text{ years}$$

0 $\nu\beta\beta$  mode highly favored over 2 $\nu\beta\beta$

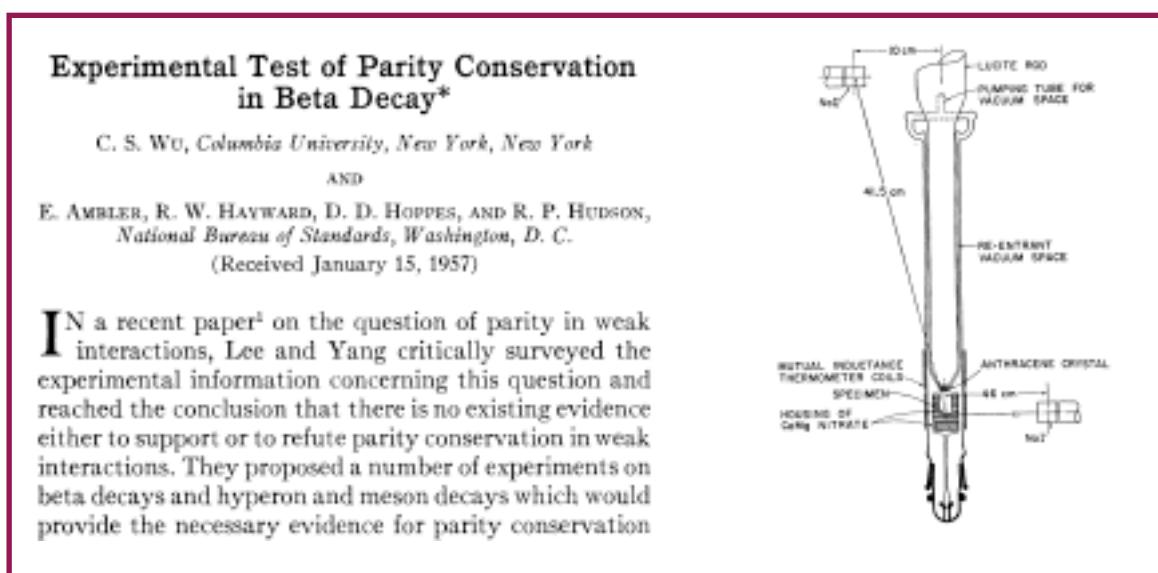
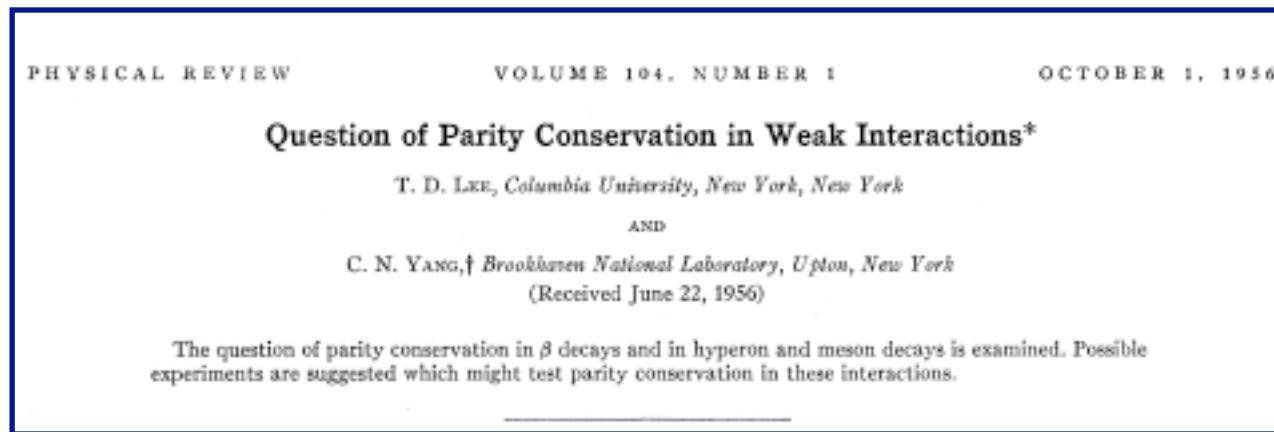
If observe  
2 $\nu\beta\beta \Rightarrow$   
neutrinos are  
Dirac



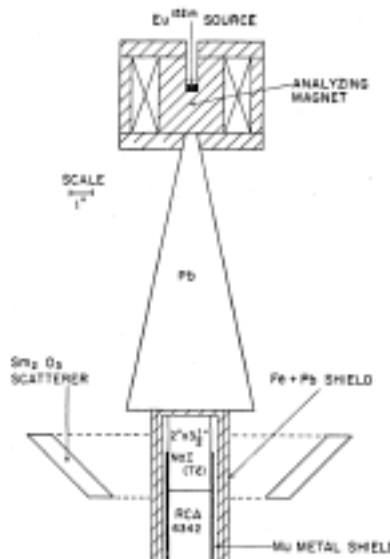
If observe  
0 $\nu\beta\beta \Rightarrow$   
neutrinos are  
Majorana

# 1956-1958 Revelations & Revolution

## Weak Interaction maximally violates parity



# 1958 Goldhaber-Grodzins-Sunyar



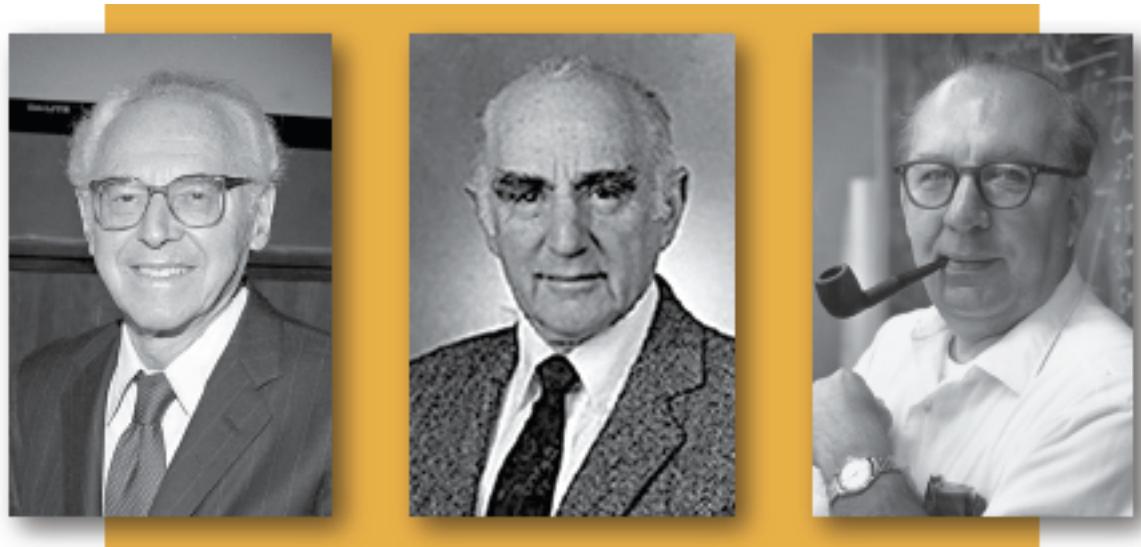
## Helicity of Neutrinos\*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

*Brookhaven National Laboratory, Upton, New York*

(Received December 11, 1957)

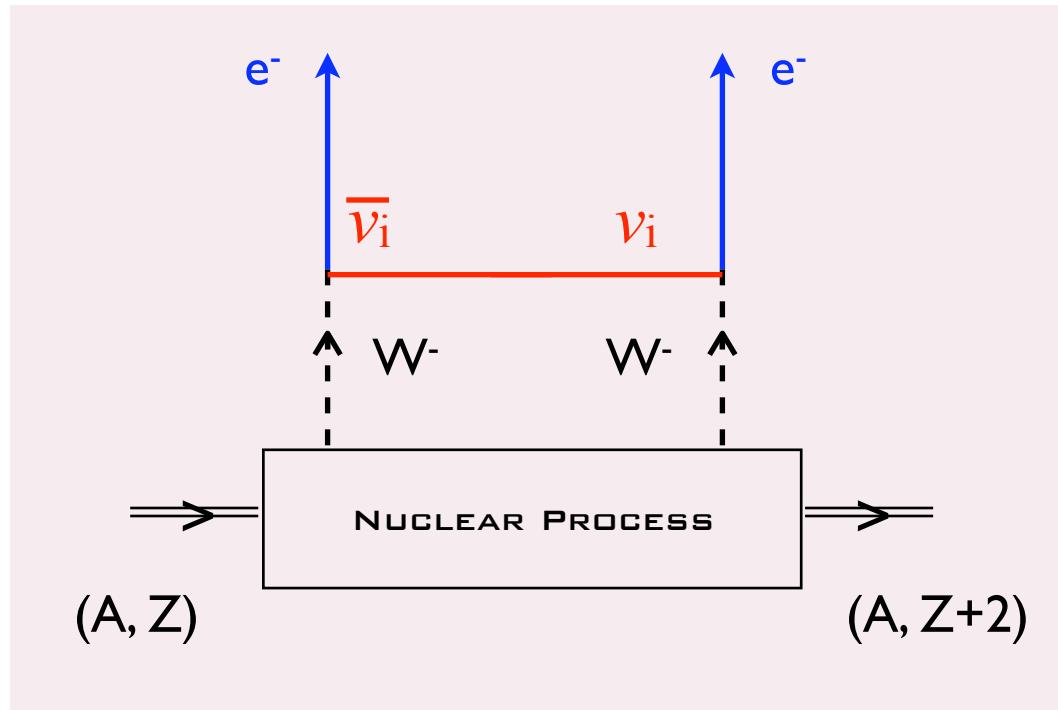
A COMBINED analysis of circular polarization and resonant scattering of  $\gamma$  rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu<sup>152m</sup>, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,<sup>1</sup> 0<sup>-</sup>, we find that the neutrino is "left-handed," i.e.,  $\sigma_\nu \cdot \hat{p}_\nu = -1$  (negative helicity).



- Weak Interaction
- maximally violates parity
- V-A nature
- neutrinos have intrinsic handedness

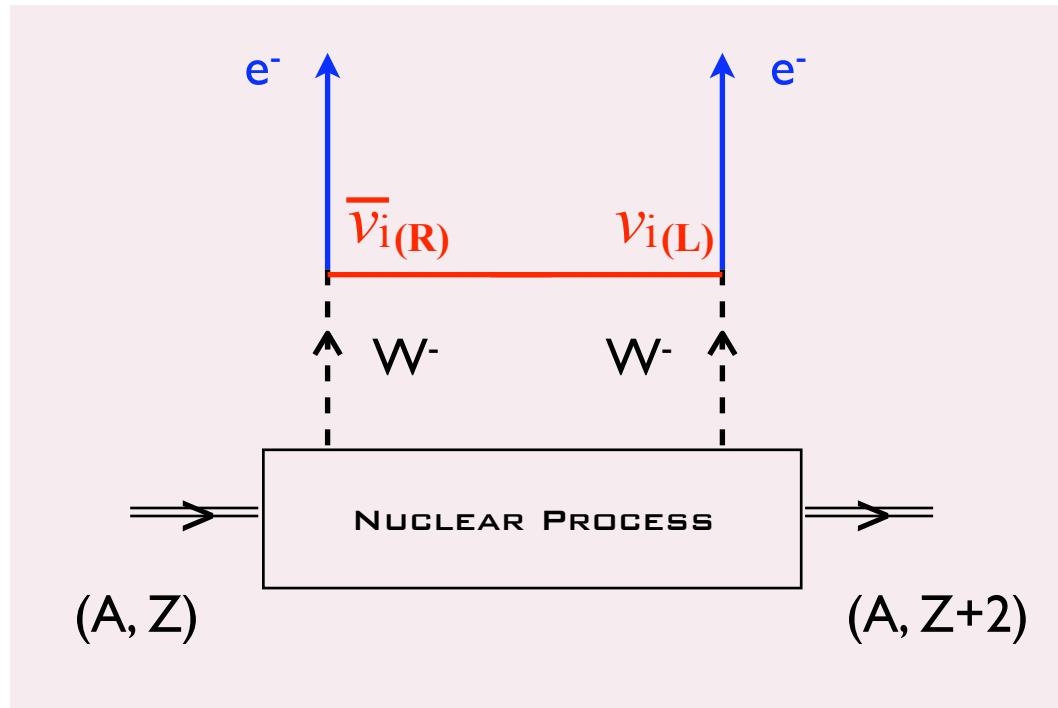
# $\nu$ Helicity and $0\nu\beta\beta$ -decay

$$n \rightarrow p + e^- + \bar{\nu}$$
$$\nu + n \rightarrow p + e^-$$



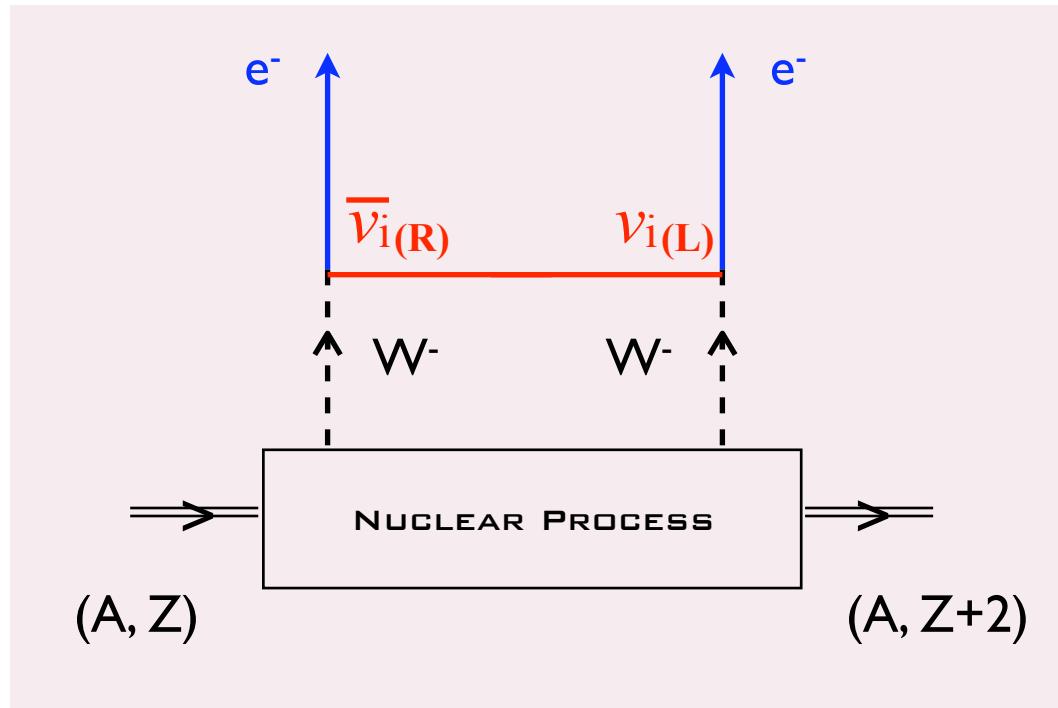
# $\nu$ Helicity and $0\nu\beta\beta$ -decay

$$n \rightarrow p + e^- + \bar{\nu}_{(R)}$$
$$\nu_{(L)} + n \rightarrow p + e^-$$



# $\nu$ Helicity and $0\nu\beta\beta$ -decay

$$n \rightarrow p + e^- + \bar{\nu}_{(R)}$$
$$\nu_{(L)} + n \rightarrow p + e^-$$



$0\nu\beta\beta$  requires in addition to Majorana neutrinos and a lepton violating interaction, a mechanism to “flip” from right handed anti-neutrino to left-handed neutrino

The transition can occur if neutrinos have mass  
“wrong-handed” helicity admixture  $\sim m_i/E_{\nu i}$

# Implications for $\beta\beta$ -decay



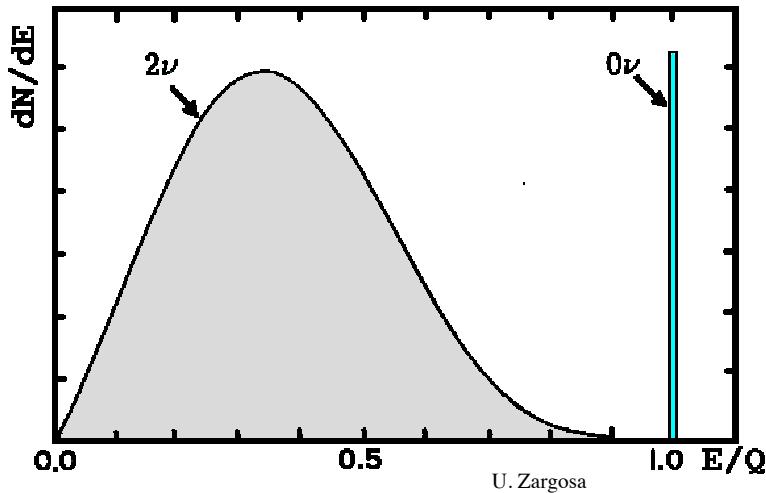
Primakoff and Rosen Rep. Prog. Phys. **22** 121 (1959)



$$\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^2 \eta^2$$

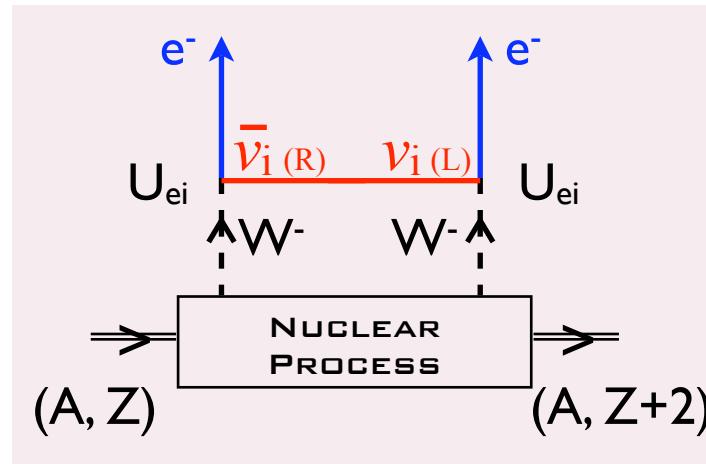
$0\nu\beta\beta$  strongly suppressed compared to  $2\nu\beta\beta$ !

Observation of  $2\nu\beta\beta$  tells one nothing about Dirac/  
Majorana nature of  $\nu$ .



- Recognized that the relative rates were “swapped”(absolute change of  $10^6$ )
- Included a serious approach to account for the Nuclear Process in calculating rates - nuclear structure, average separation between neutrons

# $0\nu\beta\beta$ Decay - Current Understanding



$$\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} |M_{0\nu}|^2 \eta^2$$

$$\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

## $0\nu\beta\beta$ Requires:

- neutrino must have non-zero mass
  - “wrong-handed” helicity admixture  $\sim m_i/E_{vi}$   
(Any process that allows  $0\nu\beta\beta$  to occur requires Majorana neutrinos with non-zero mass.  
Schechter and Valle, 1982)
- Lepton number violation
  - No experimental evidence that Lepton number is conserved  
(i.e. general SM principles, such as electroweak-isospin conservation and renormalizability)

$$Amp[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^2 \right| \equiv \langle m_{\beta\beta} \rangle$$

Given that neutrinos have non-zero mass - if  $0\nu\beta\beta$  decay is observed  $\Rightarrow$  neutrinos are Majorana particles

# Underlying $0\nu\beta\beta$ Decay Mechanisms

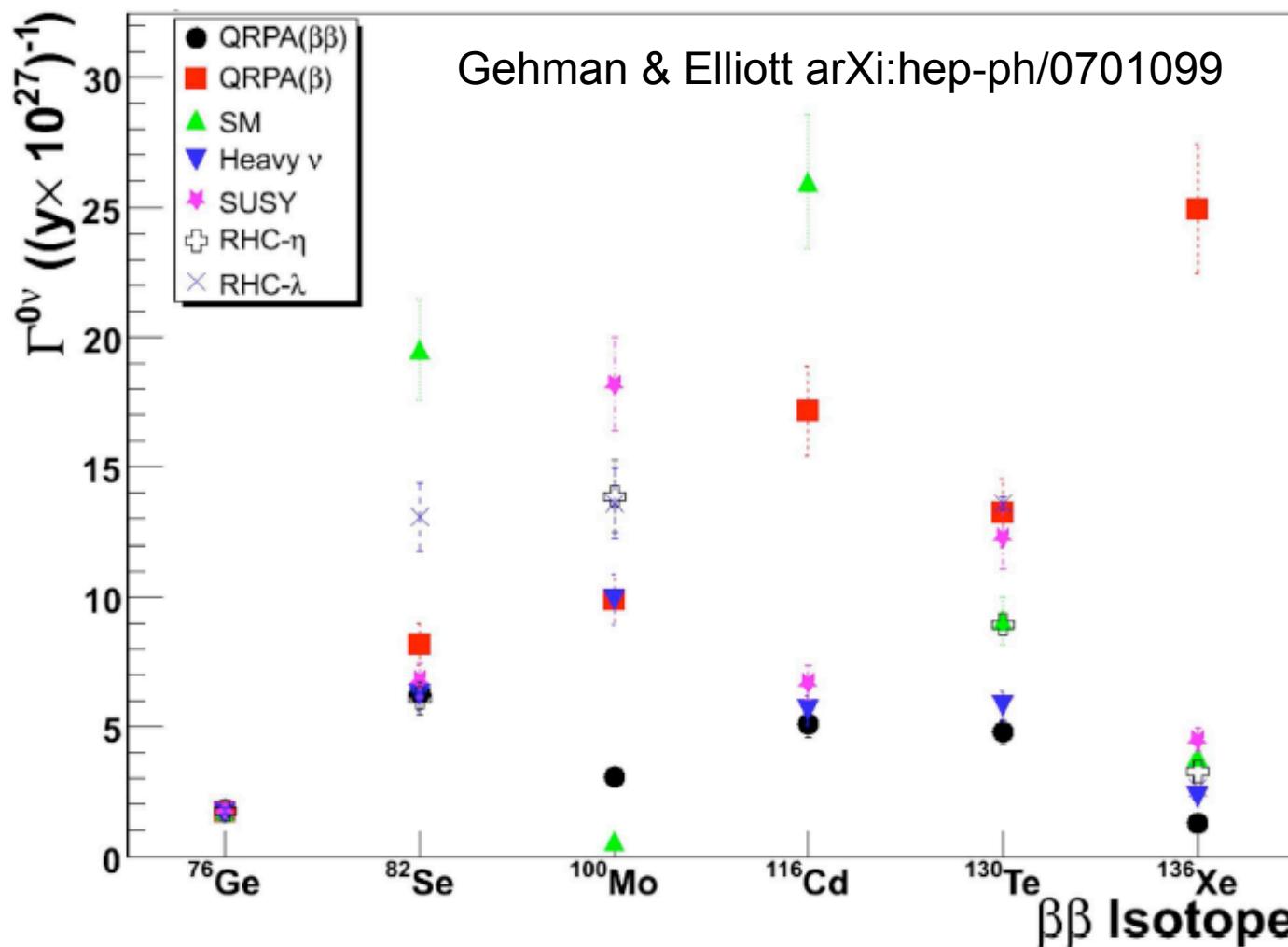
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} \left|M_{0\nu}\right|^2 \left\langle m_{\beta\beta} \right\rangle^2 = G_{0\nu} \left|M_{0\nu}(\eta)\right|^2 \eta^2$$

There are many possible underlying mechanisms for  $0\nu\beta\beta$  decay  
(with Lepton violating interactions ( $\eta$ ))

- light Majorana neutrino exchange
- heavy Majorana neutrino exchange
- right-handed currents (RHC)
- exchange mechanisms arising from R-Parity violating supersymmetry models.
- 
- 
-

# $0\nu\beta\beta$ -decay as a Probe of LV Interactions

If  $0\nu\beta\beta$  is observed, then measurements on 3-4 multiple isotopes might be able to distinguish potential physics mechanisms



Comparison assumes a single dominant mechanism.

Requires results from 3-4 isotopes & calculation of NME to ~20%

Also see  
Deppisch & Päs  
arXiv:hep-ph/0612165

# Constraints on $\nu$ mass and $0\nu\beta\beta$ -decay

## What we know

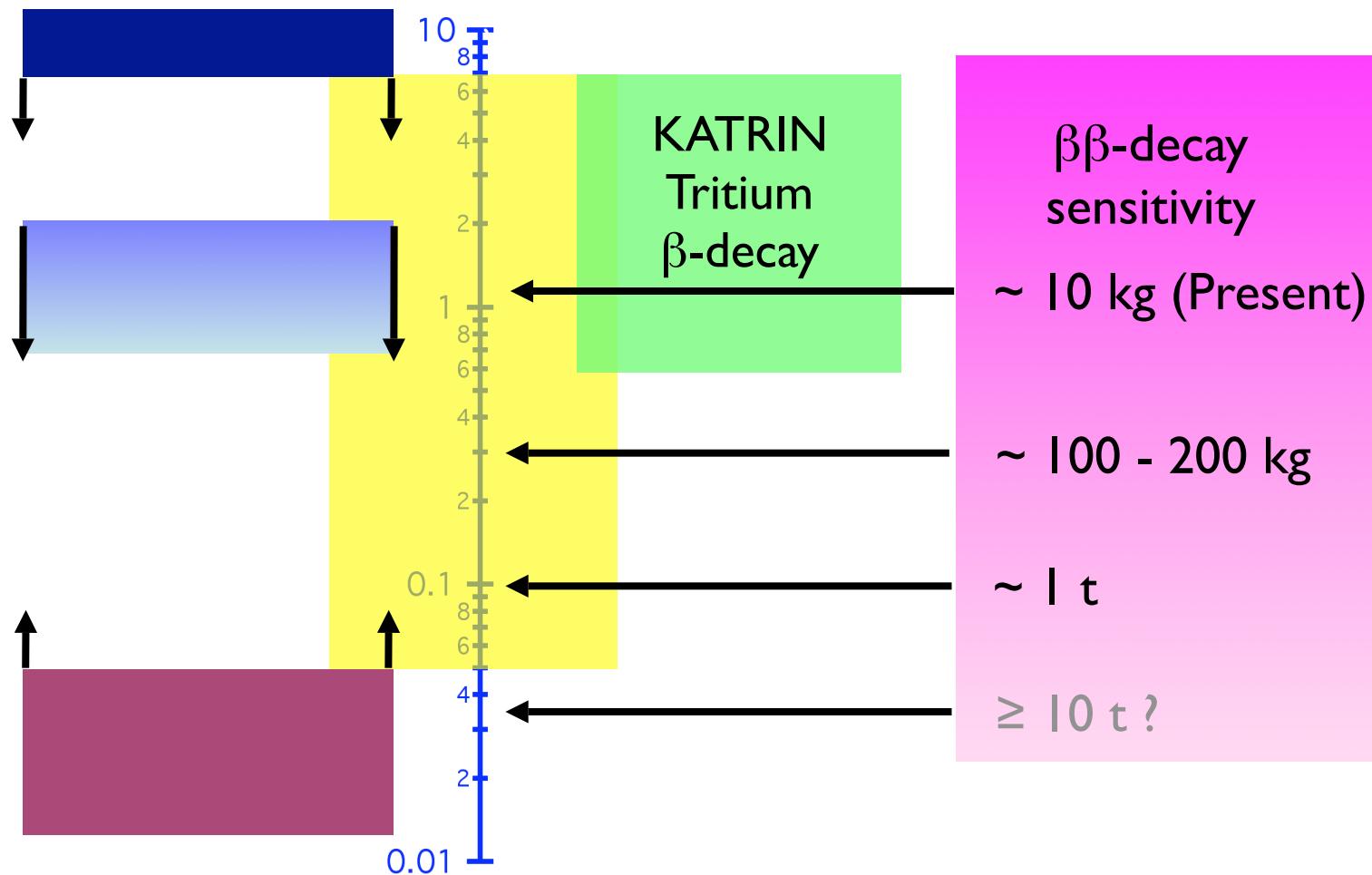
Upper Bound  
Tritium  $\beta$ -decay  
(Mainz)

Upper Bound  
Cosmology  
(WMAP, 2dF,  
Lyman- $\alpha$ )

Lower Bound  
Atm.  $\nu$  (SuperK)

$\Sigma m_\nu$

## Future Experiments



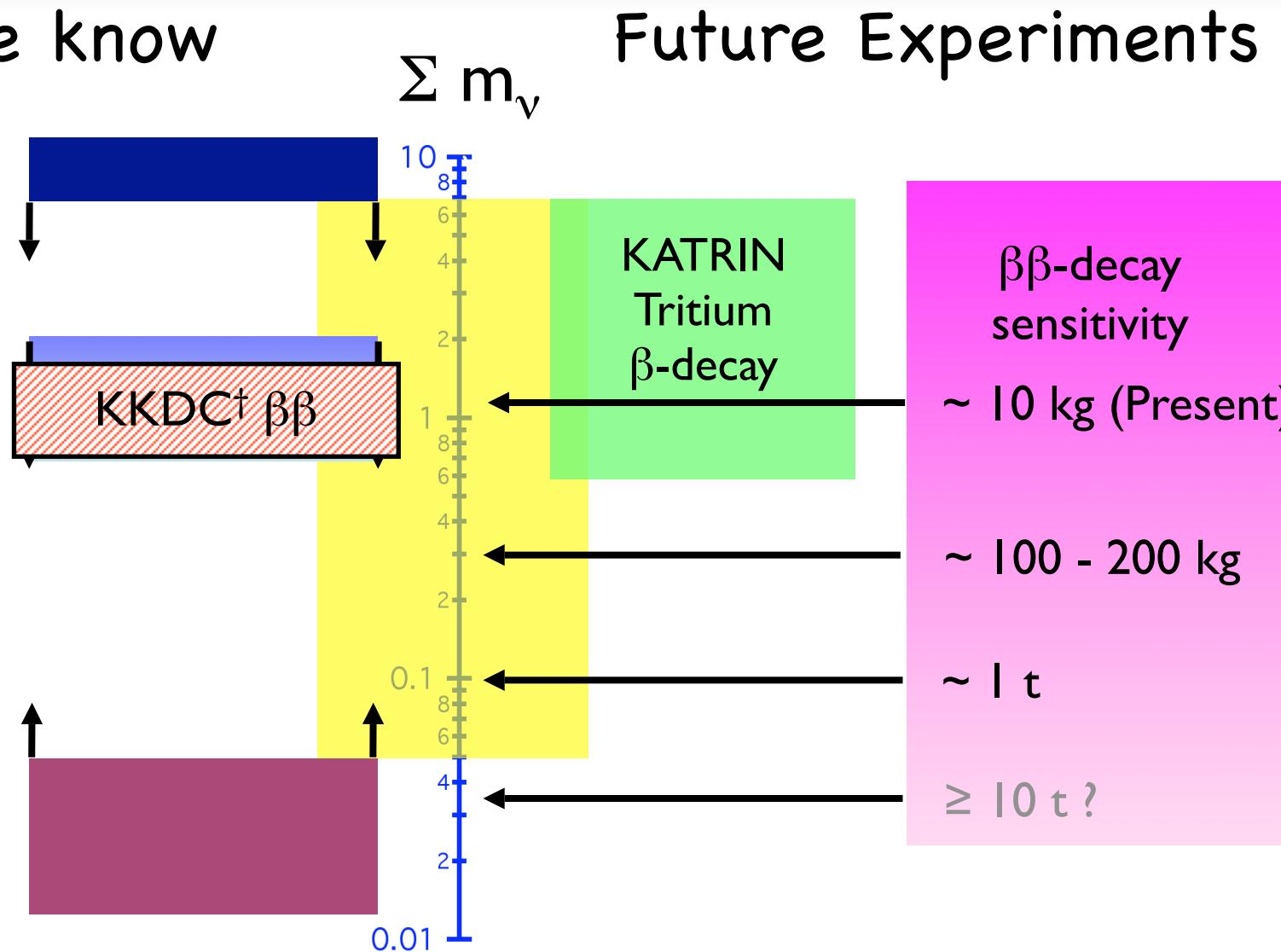
# Constraints on $\nu$ mass and $0\nu\beta\beta$ -decay

## What we know

Upper Bound  
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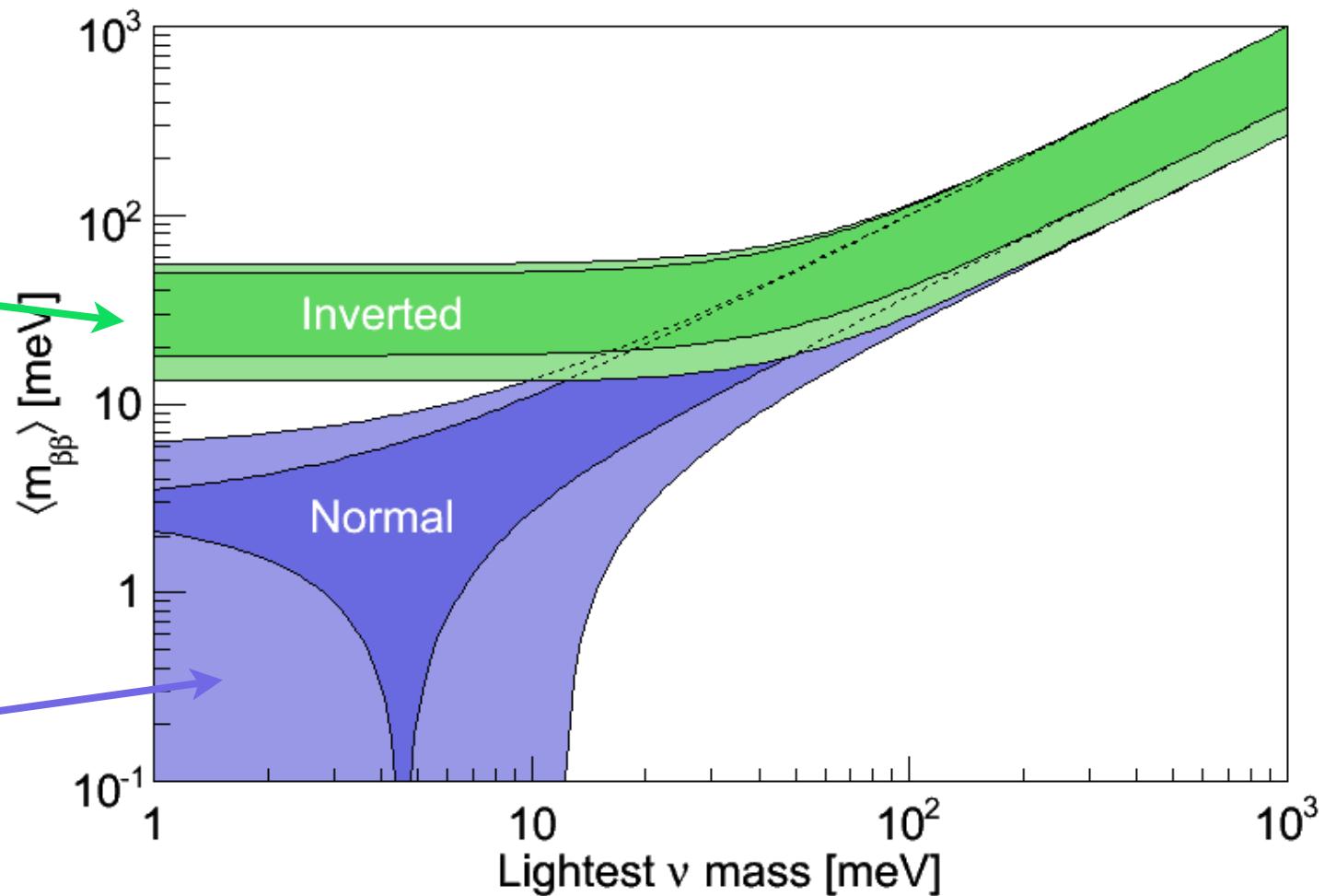
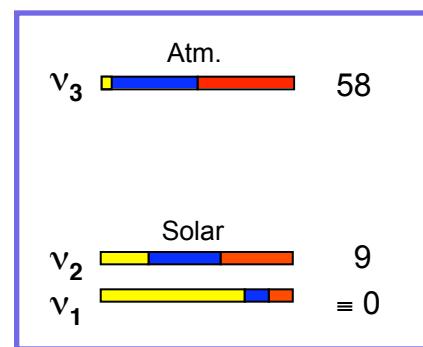
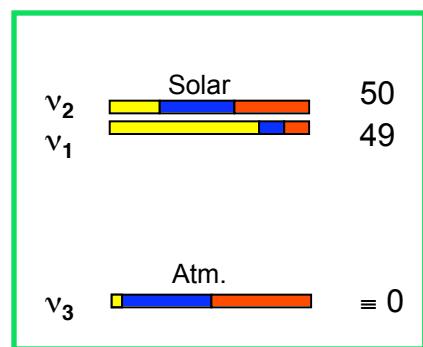
† Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett. B* **586** 198 (2004).

# $0\nu\beta\beta$ Decay Sensitivity to $\langle m_{\beta\beta} \rangle$

Assuming LV mechanism is light Majorana neutrino exchange

$0\nu\beta\beta$  limits for:  $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{128}\text{Te}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

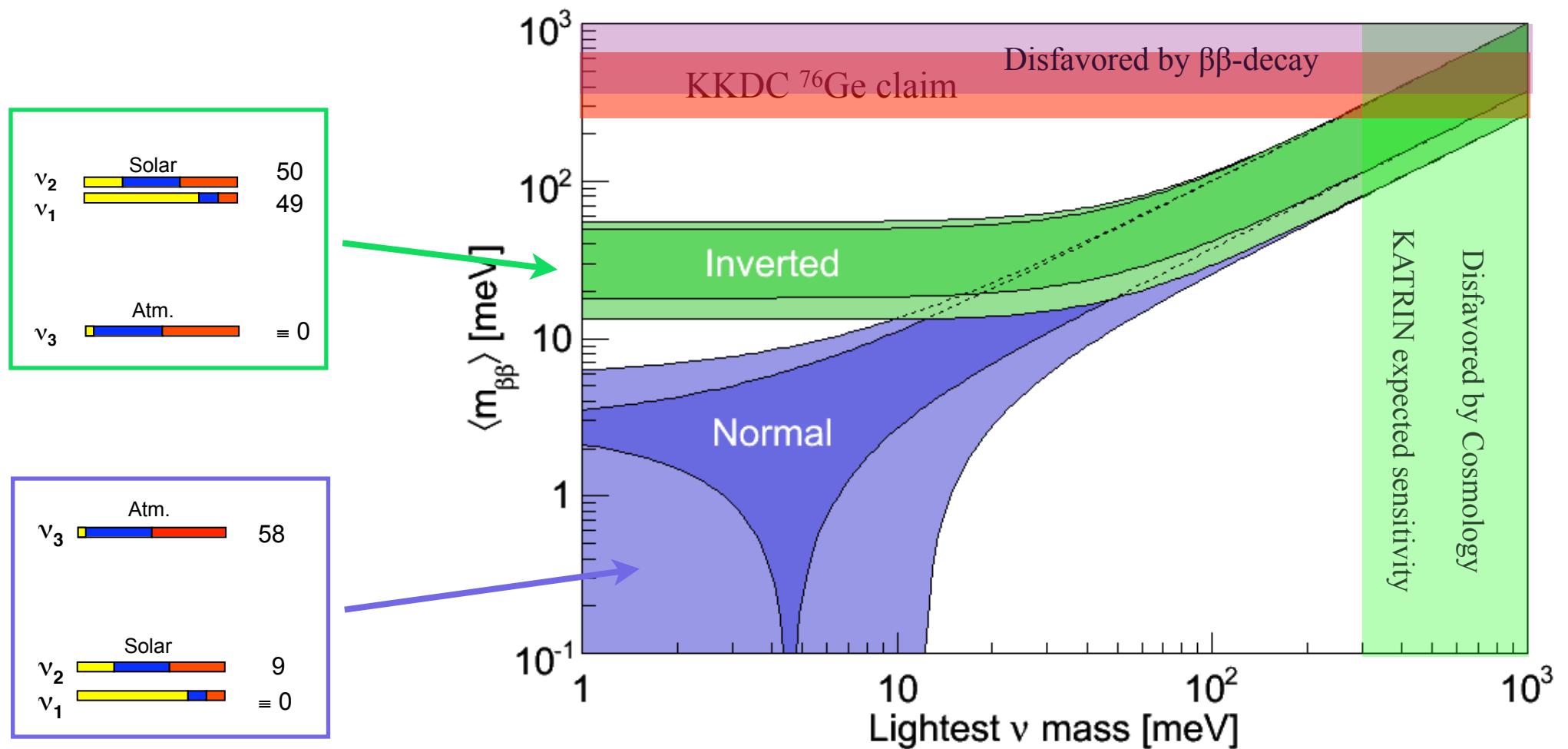


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$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$



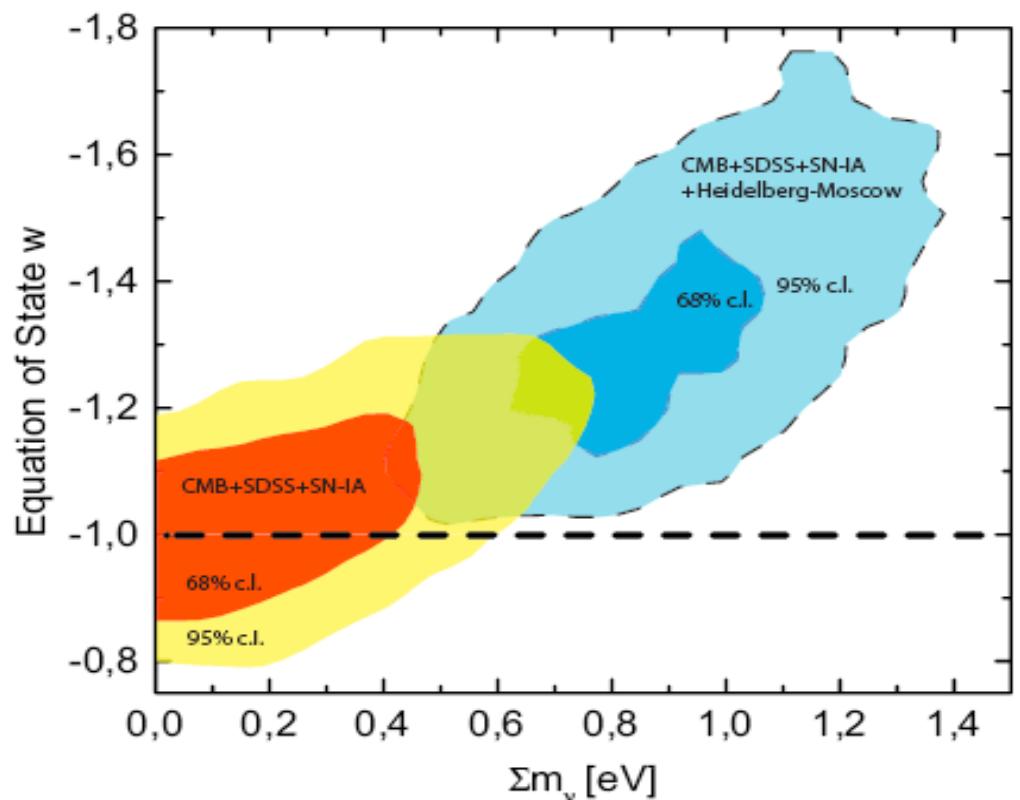
# Complementarity of $\nu$ mass measurements

What if one observes  $0\nu\beta\beta$  at a larger value than for example that found from cosmology?

- Effective majorana mass (the decay amplitude) might not arise from the exchange of light Majorana neutrinos.
- Underlying model dependent assumptions of the cosmological model may be incorrect.

De La Macorra, Melchiorri,  
Serra, & Bean  
arXiv astro-ph/0608351

If Klapdor-Kleingrothaus (KKDC) is correct then a global analysis (blue) implies that the Dark Energy equation of state,  $w$ , must be more negative than -1.

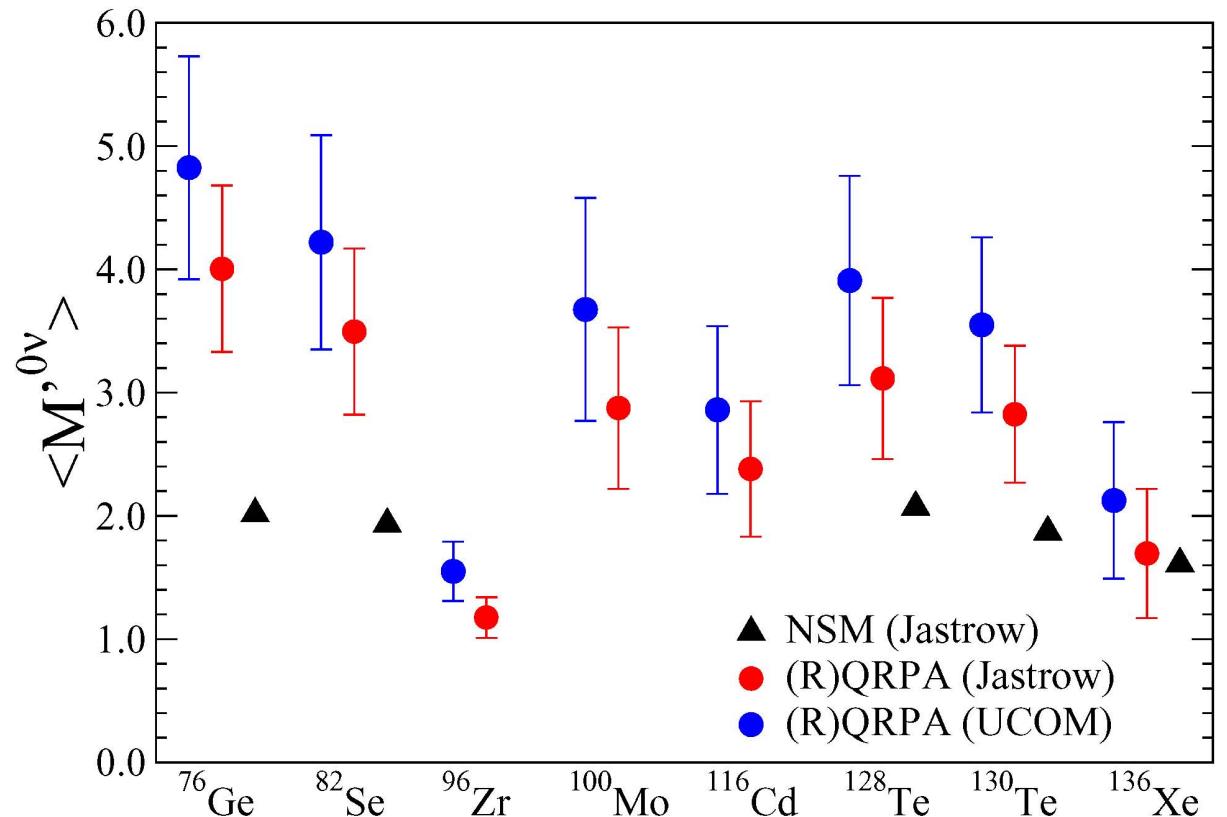


# Nuclear Matrix Elements

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} \left|M_{0\nu}\right|^2 \langle m_{\beta\beta} \rangle^2$$

Extracting an effective neutrino mass requires an understanding of the nuclear matrix elements (NME) at about the 20% theoretical uncertainty level.

NME are calculated using two different techniques, the Shell Model and Quasi-random phase approximation (QRPA)

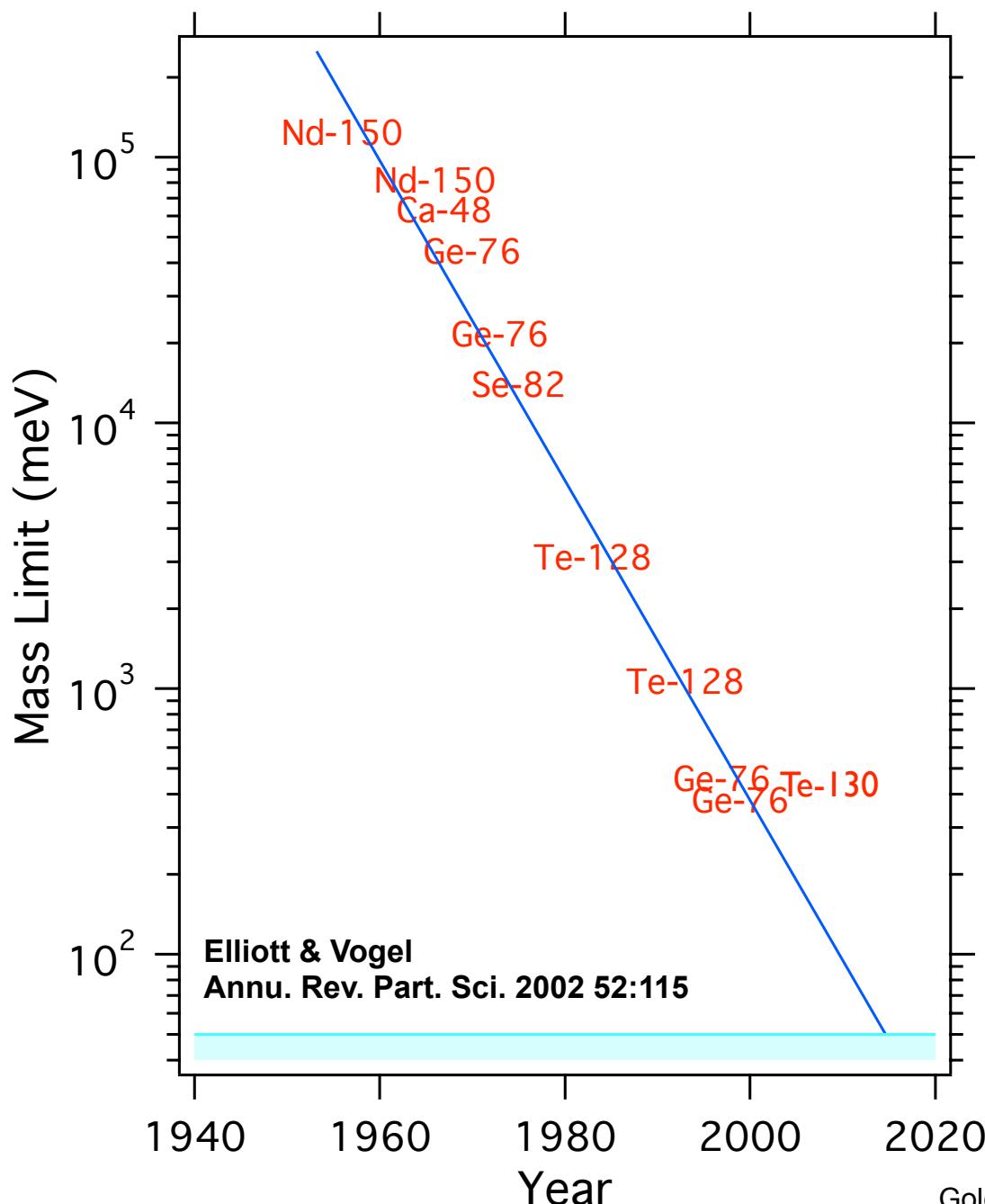


QRPA: Nucl. Phys. A, 766 107 (2006)

LSSM: From Poves NDM06 talk (Caurier, Nowacki, Poves)

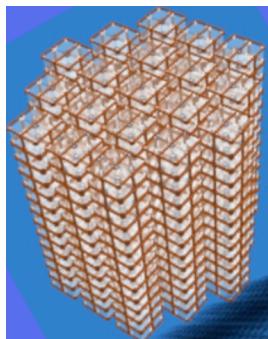
Simkovic et al. arXiv:0710.2055

# $0\nu\beta\beta$ Progress & Best Limits

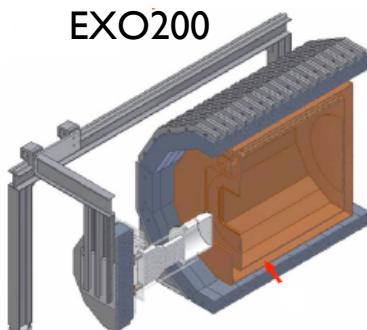


# $0\nu\beta\beta$ decay Experiments - Efforts Underway

CUORE



EXO200



NEMO



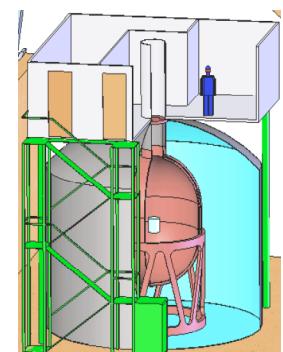
Collaboration	Isotope	Technique	Mass	Status
CAMEO	Cd-116	CdWO <sub>4</sub> crystals	1 t	
CANDLES	Ca-48	60 CaF <sub>2</sub> crystals in liq. scint	6 kg	Construction
CARVEL	Ca-48	<sup>48</sup> CaWO <sub>4</sub> crystal scint.	100 kg	
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUROICINO	Te-130	TeO <sub>2</sub> Bolometer	11 kg	Operating
CUORE	Te-130	TeO <sub>2</sub> Bolometer	206 kg	Construction
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
EXO200	Xe-136	Xe TPC	200 kg	Construction
EXO	Xe-136	Xe TPC	1-10t	R&D
GEM	Ge-76	Ge diodes in LN	1 t	
GERDA	Ge-76	Seg. and UnSeg. Ge in LAr	35-40 kg	Construction
GSO	Gd-160	Gd <sub>2</sub> SiO <sub>5</sub> :Ce crystal scint. in liquid scint	2t	
HPXeTPC	Xe-136	High Pressure TPC	1t	R&D
Majorana	Ge-76	Segmented Ge	60 kg 1 t	Proposed Future
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Operating
SuperNEMO	Se-82	Foils with tracking	100 kg	Proposed
MOON	Mo-100	Mo sheets	200 kg 1 t	R&D
SNO+ $\beta\beta$	Nd-150	0.1% suspended in Scint.	56 kg	R&D
Xe	Xe-136	Xe in liq. Scint.	1.56 t	
XMASS $\beta\beta$	Xe-136	Liquid Xe	10 kg	Feasibility

Operating

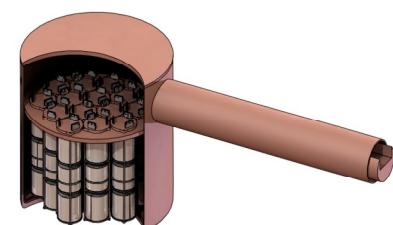
Construction

Proposed/R&D

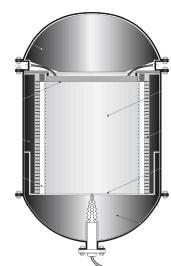
GERDA



MAJORANA



HPXeTPC



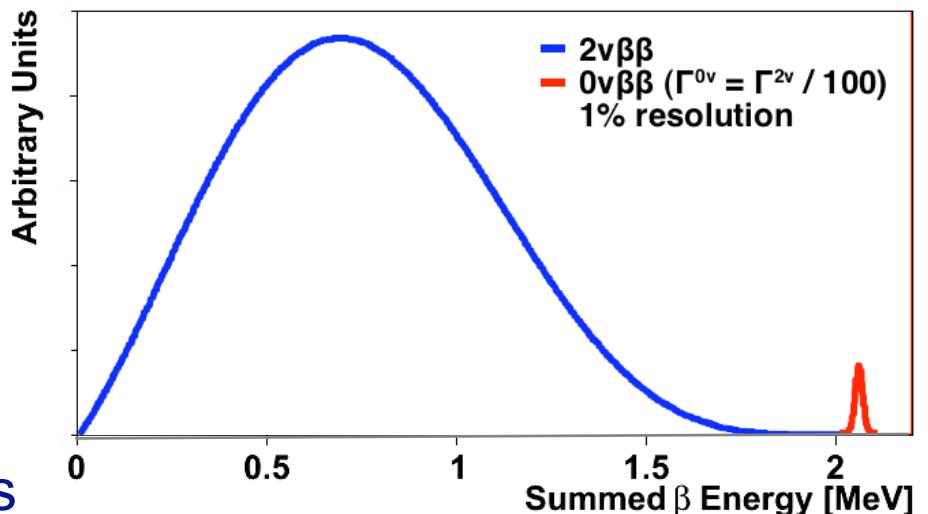
# Experimental Considerations

*Extremely slow decay rates*

( $0\nu\beta\beta T_{1/2} \sim 10^{26} - 10^{27}$  years)

Best case,  
0 background !

$\propto$  Source Mass • time<sub>exp</sub>



Requires

Large, highly efficient source mass

- detector as source

Best possible energy resolution

- minimize  $0\nu\beta\beta$  peak ROI to maximize S/B
- separate from  $0\nu\beta\beta$  from irreducible  $2\nu\beta\beta$  ( $\sim T_{1/2} \sim 10^{19} - 10^{21}$  years)

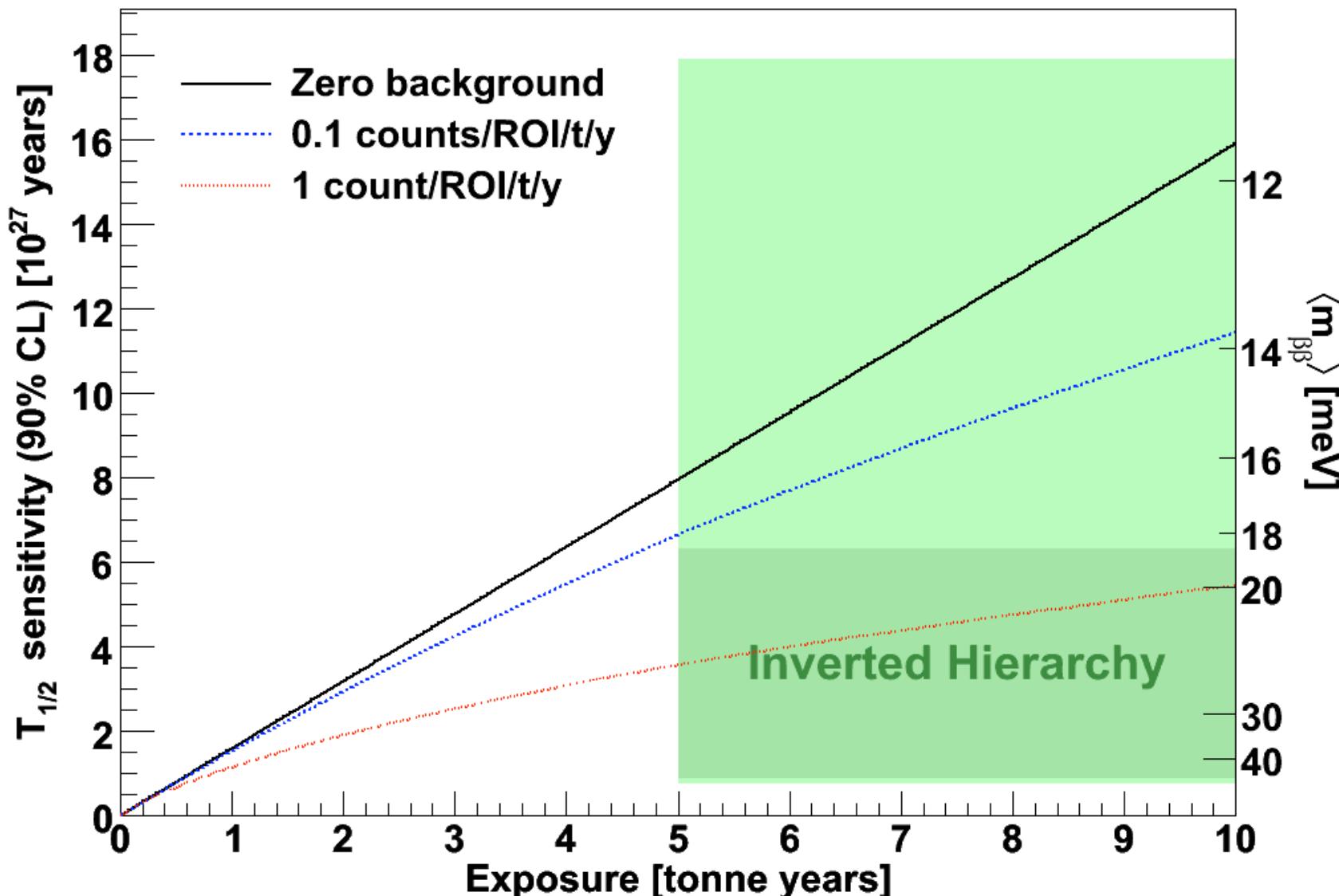
Extremely low (near-zero) backgrounds in the  $0\nu\beta\beta$  peak region

- **Goal: counts/tonne-year in the region of interest**
- requires ultra-clean radiopure materials
- the ability to discriminate signal from background

# Sensitivity and backgrounds

1-tonne  $^{76}\text{Ge}$  Example

$$T_{1/2}^{\text{0v}} = \ln(2)N\bar{\epsilon}t/\text{UL}(B)$$



# “Ideal” Experiment

Source serves as the detector

Elemental (enriched) source to minimize active material.

Large Q value - faster  $\bar{\nu}$  rate and also places the region of interest above many potential backgrounds.

Relatively slow  $2\nu\beta\beta$  rate helps control this irreducible background.

Direct identification of the decay progeny in coincidence with the  $0\nu\beta\beta$  decay eliminates all potential backgrounds except  $2\nu\beta\beta$ .

Full Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use  $2\nu\beta\beta$ )

Spatial resolution and timing information to reject background processes.

Demonstrated technology at the appropriate scale.

The nuclear theory is better understood in some isotopes than others.

The interpretation of limits or signals might be easier to interpret for some isotopes.

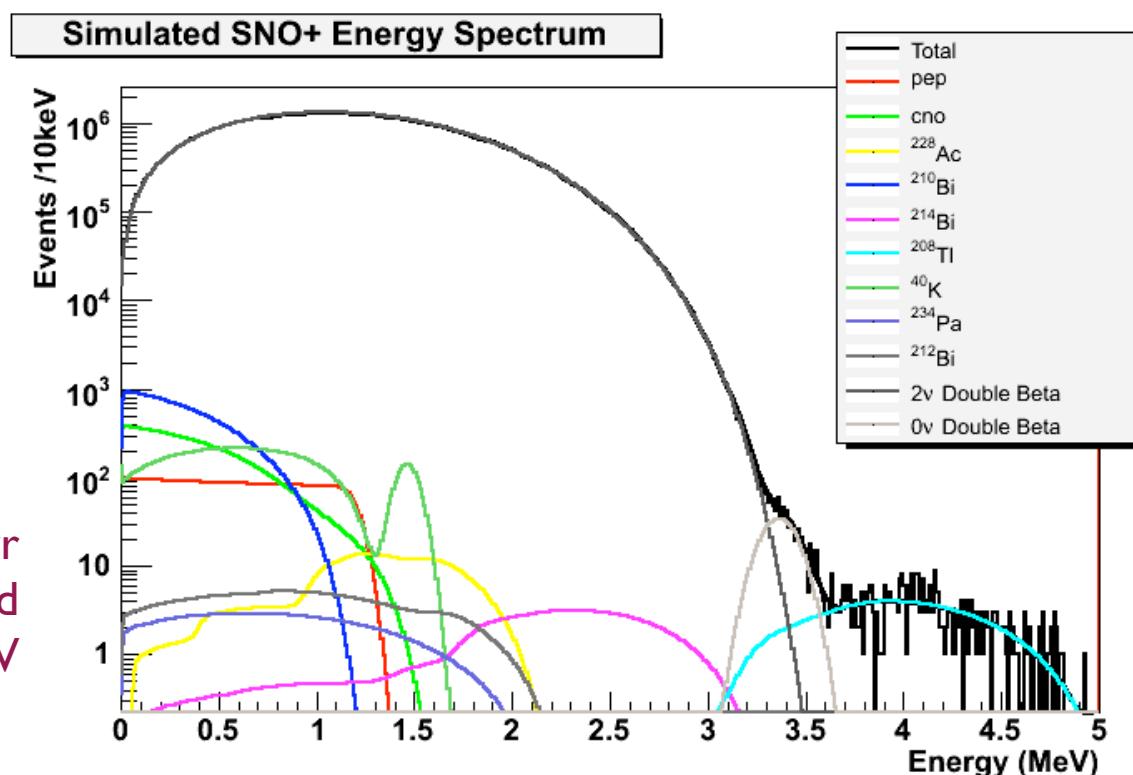
**No one ideal isotope or experimental technique**

# SNO+ (Canada - U.S. - U.K. - Germany -Portugal)

## Science : Neutrinoless Double Beta-decay, Geoneutrinos, Solar ν

- $^{150}\text{Nd}$  (5.6% abundance) 0.1% loaded in scintillator.
- Initial plan is to use 1 ton of  $^{\text{nat}}\text{Nd}$  (56 kg of  $^{150}\text{Nd}$ )
- Located at SNOLAB
- Utilizes substantial investment in SNO
- Initial success in loading into pseudocumene and also in linear alkylbenzene
- Technical challenge - available light with loaded scintillator
- Considering enrichment option

1 yr  
500 kg of  $^{150}\text{Nd}$   
 $\langle m_{ee} \rangle = 150 \text{ meV}$

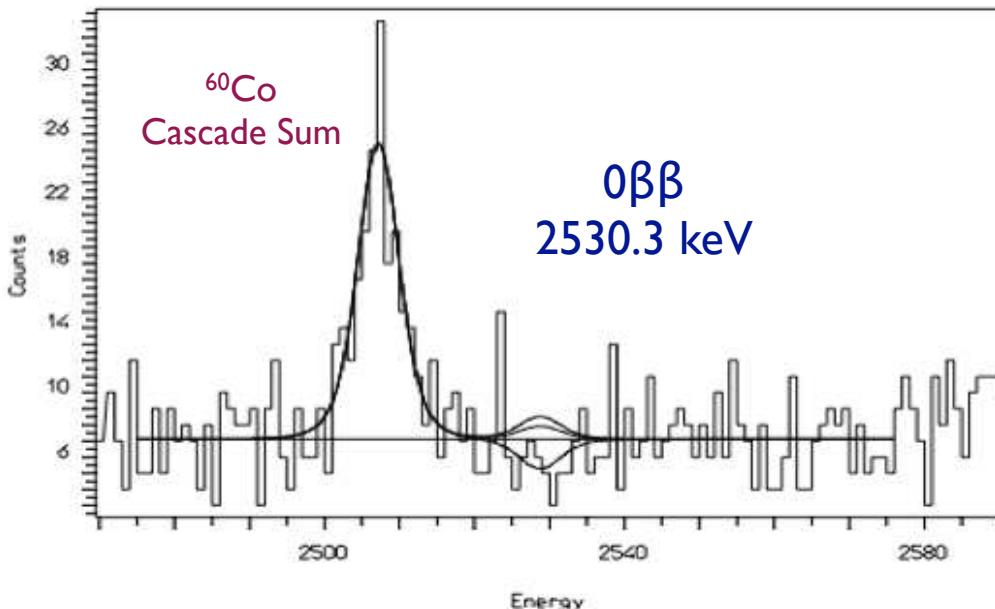


# CUORE (Italy - Spain - U.S.)

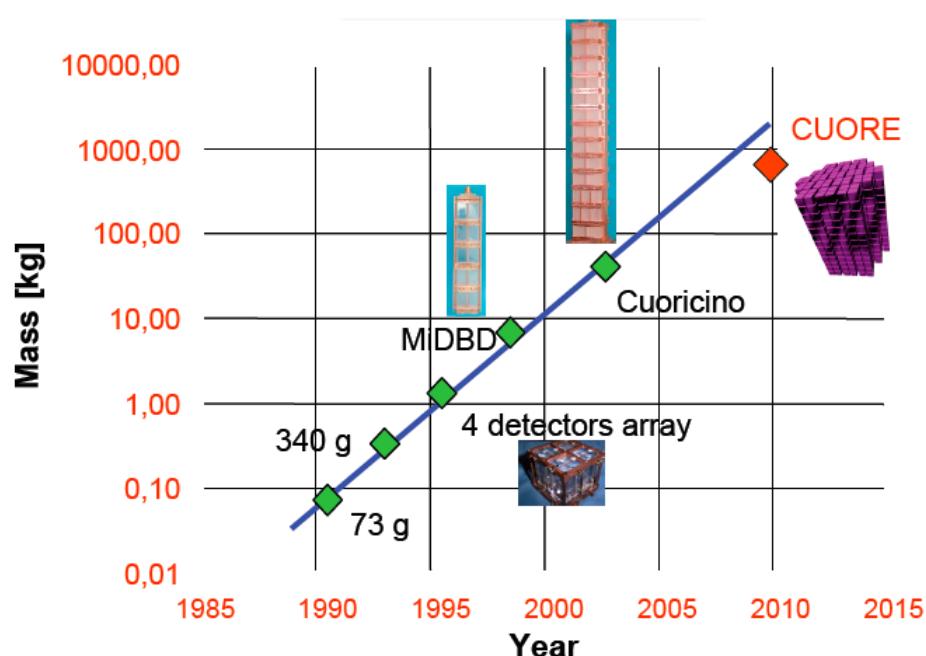
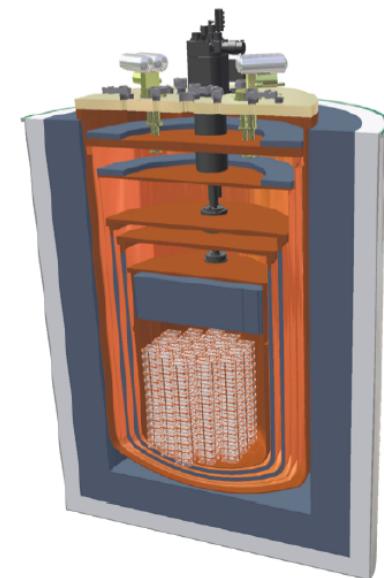
- $^{130}\text{Te}$  (34% abundance) bolometer.
- Array of 988  $\text{TeO}_2$  crystals
- Expects to operate in Gran Sasso by 2011
- Builds upon success of Cuoricino

11.83 kg of  $^{130}\text{Te}$ , April 2003-2006

$T_{1/2} > 3.0 \times 10^{24} \text{ y}$  (90% CL)



Neutrinoless Double Beta Decay

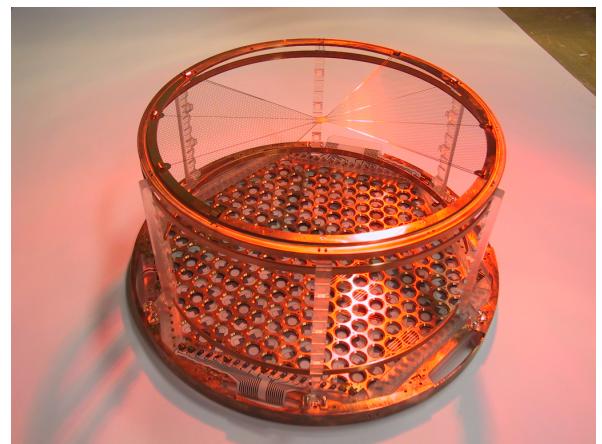
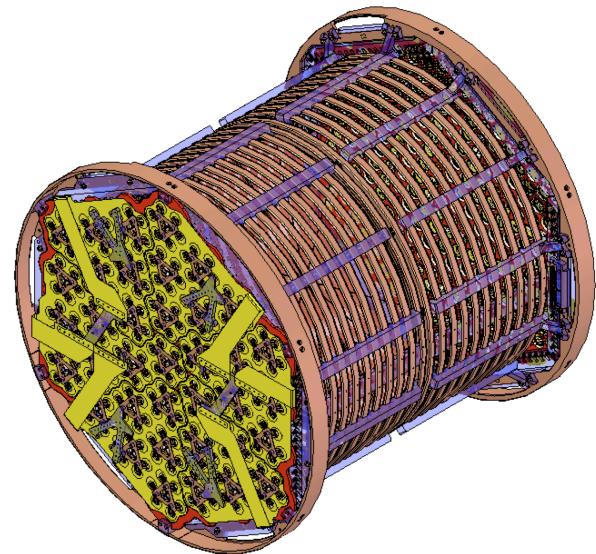


Goldhaber-Grodzins-Sunyar Celebration



# EXO-200 (U.S., Canada, Russia, Switzerland)

- 200 kg of 80% enriched  $^{136}\text{Xe}$
- Liquid time-projection chamber
- Uses charge and light collection 1.6% resolution
- Expects to operate in WIPP by 2009
- Aims to measure  $2\nu\beta\beta$  mode (not yet observed)



# EXO tonne scale with Ba tagging

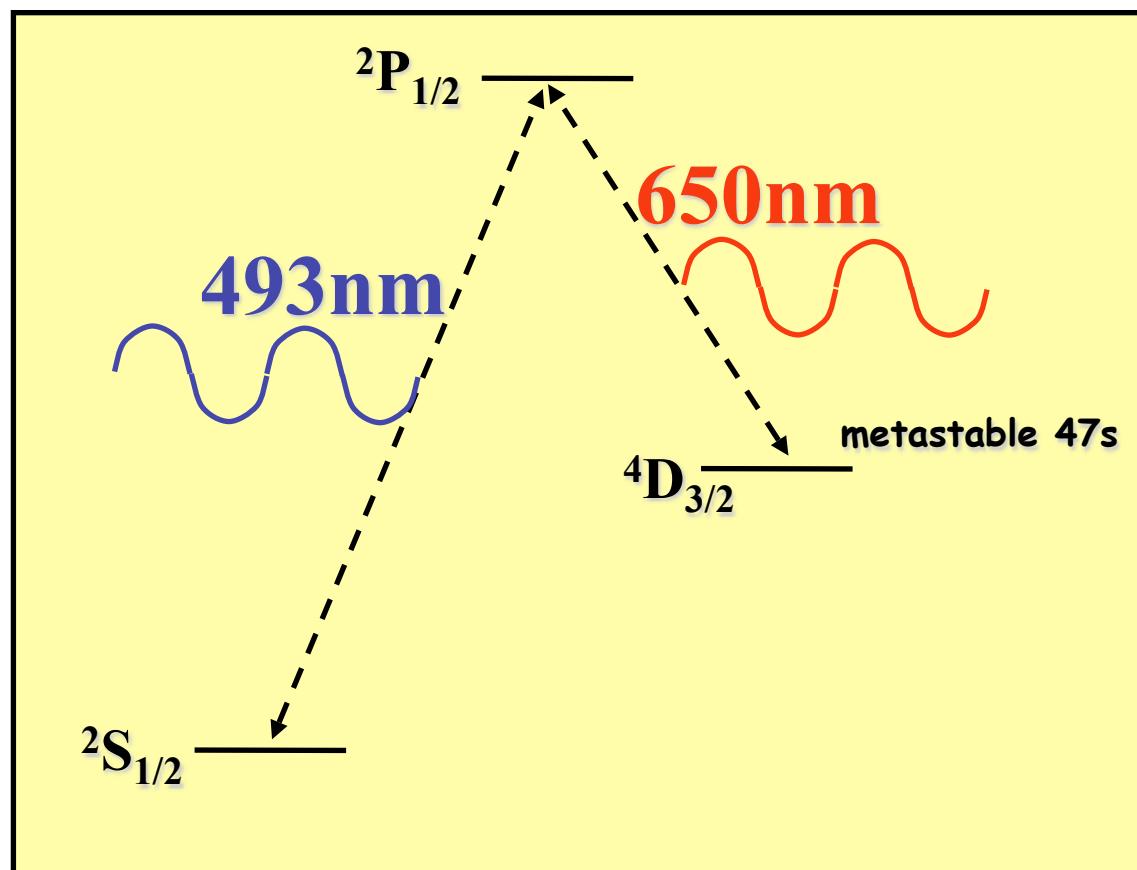
Xe offers a qualitatively new tool against background:  
 $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} e^- e^-$  final state can be identified  
 using optical spectroscopy (M.Moe PRC44 (1991) 931)

Ba<sup>+</sup> system best studied  
 (Neuhauser, Hohenstatt,  
 Toshek, Dehmelt 1980)

Very specific signature  
 "shelving"

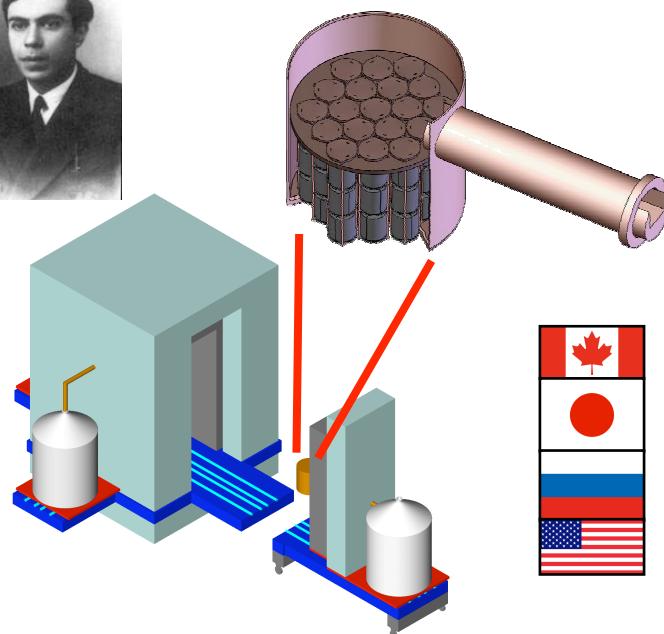
Single ions can be detected  
 from a photon rate of  $10^7/\text{s}$

Important additional constraint  
 Dramatic Background reduction

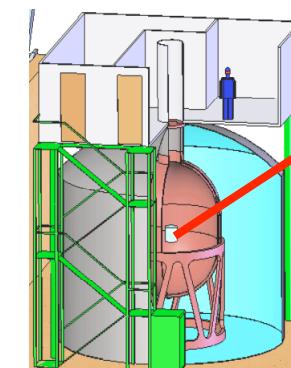


# $^{76}\text{Ge}$ - MAJORANA and GERDA

- 86% enriched Hyper-pure  $^{76}\text{Ge}$  crystals
- 0.16 % resolution
- best  $0\nu\beta\beta$ -decay sensitivity to date



- ${}^{\text{enr}}\text{Ge}$  modules in electroformed Cu cryostat, Cu / Pb passive shield
- $4\pi$  plastic scintillator  $\mu$  veto
- Demonstrator: 30 kg  ${}^{\text{enr}}\text{Ge}$ /30 kg  ${}^{\text{nat}}\text{Ge}$



- ${}^{\text{enr}}\text{Ge}$  array submersed in LAr
- Water Cherenkov  $\mu$  veto
- Phase I:  $\sim 18$  kg (H-M/IGEX xtals)
- Phase II: +20 kg segmented xtals

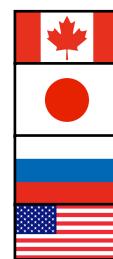
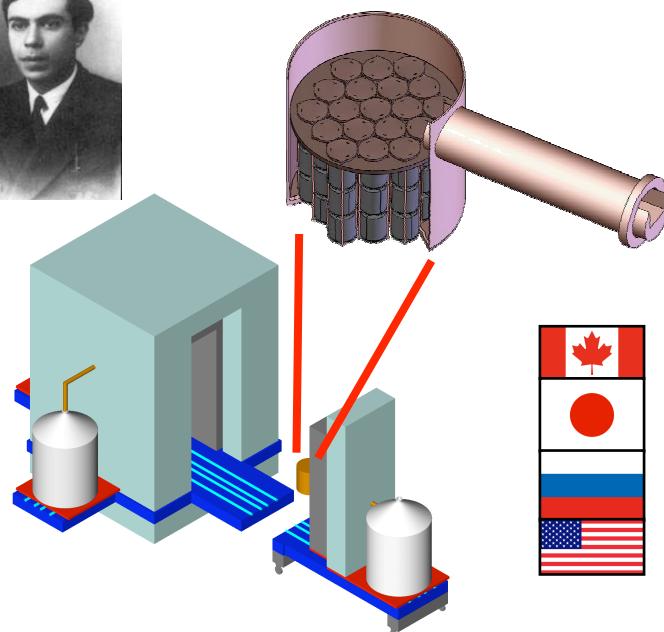
# $^{76}\text{Ge}$ - MAJORANA and GERDA

## Joint Cooperative Agreement:

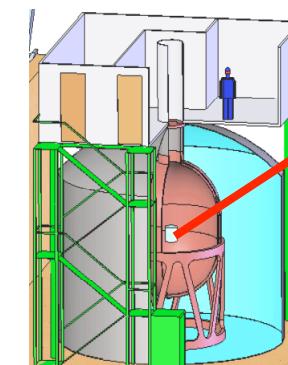
Open exchange of knowledge & technologies (e.g. MaGe, R&D)

Intention to merge for larger scale 1-tonne exp.

Select best techniques developed and tested in GERDA and MAJORANA



- ${}^{\text{enr}}\text{Ge}$  modules in electroformed Cu cryostat, Cu / Pb passive shield
- $4\pi$  plastic scintillator  $\mu$  veto
- Demonstrator: 30 kg  ${}^{\text{enr}}\text{Ge}$ /30 kg  ${}^{\text{nat}}\text{Ge}$



- ${}^{\text{enr}}\text{Ge}$  array submersed in LAr
- Water Cherenkov  $\mu$  veto
- Phase I:  $\sim 18$  kg (H-M/IGEX xtals)
- Phase II: +20 kg segmented xtals

# The MAJORANA $^{76}\text{Ge}$ Demonstrator



$^{76}\text{Ge}$  offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best  $0\nu\beta\beta$  sensitivity to date)

- 60-kg of Ge detectors

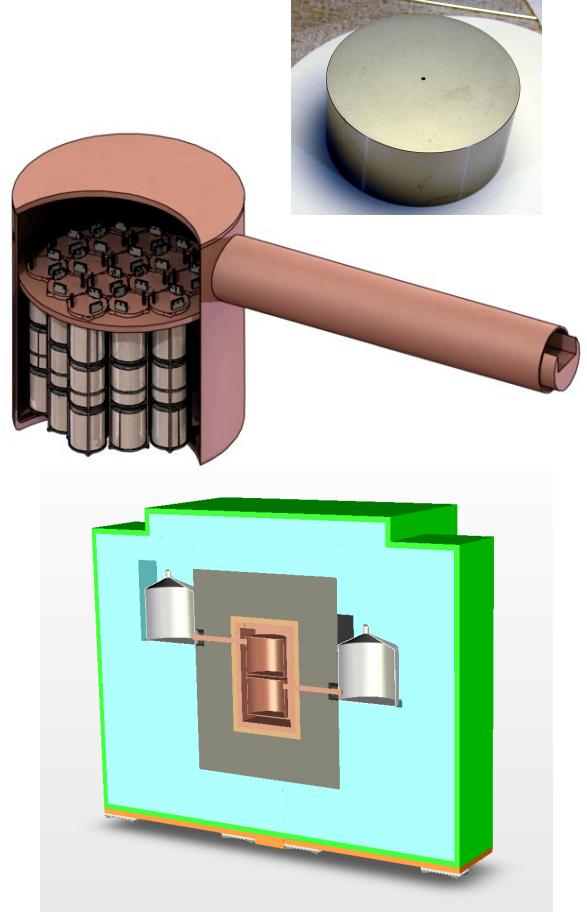
- 30-kg of 86% enriched  $^{76}\text{Ge}$  crystals required for science goal; 60-kg for background sensitivity
- Examine detector technology options p- and n-type, segmentation, point-contact.

- Low-background Cryostats & Shield

- ultra-clean, electroformed Cu
- naturally scalable
- Compact low-background passive Cu and Pb shield with active muon veto

- Located underground 4850' level at Sanford Lab (Homestake)

- Background Goal in the  $0\nu\beta\beta$  peak region of interest (4 keV at 2039 keV) ~ 1 count/ROI/t-y (after analysis cuts)



# Discovery of $0\nu\beta\beta$ -decay

- **Strong evidence** : a combination of
  - Correct peak energy
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Full energy spectrum understood
- **Further confirmation**: more difficult
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay
- **Irrefutable**
  - Observe the process in several isotopes, using a variety of experimental techniques

# Summary

- The observation of  $0\nu\beta\beta$ -decay would demonstrate Lepton number violation and indicate that neutrinos are Majorana particles - **constituting a major discovery.**
  - Needs to be confirmed from independent experiments using different isotopes and measurement techniques.
- If  $0\nu\beta\beta$ -decay is observed then it opens an exquisitely sensitive window to search for physics beyond the Standard model.
  - Measurement of  $\langle m_{\beta\beta} \rangle$  is complementary to direct and cosmological measurements of neutrino mass.
  - Measurements in different isotopes should provide insights into the underlying physics process(es).

Over the past 50 years there have been dramatic changes in our understanding of the of nuclear and particle physics, yet  $0\nu\beta\beta$ -decay remains extremely relevant as we endeavor to elucidate the underlying framework of our universe.